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Objective

- **Obtain valid data describing aircraft, inlet, and engine behavior beyond the normal operating regime of controlled flight.**
- **Explore the consequence for engine operation at extreme attitudes.**

The F/A-18A High Alpha Research Vehicle (HARV) provides the ideal platform for controlled exploration of inlet characteristics related to high-agility vehicles at full scale. The standard of instrumentation was established with this goal in mind. The HARV provided the ability to measure the inlet characteristics during departed flight and identify factors which could cause engine instability if any should occur. This effort is believed to be the first time in the industry that particular attention has been made to the acquisition of valid high-response inlet data during departed flight maneuvers.

Approach

- **Preflight rehearsals conducted on NASA flight simulator.**
- **Data acquisition of aircraft, inlet, and engine parameters was consistent with the techniques described by the other papers detailing the work in the HARV Inlet Research Program.**

The use of the flight simulator established the techniques for achieving target levels of aircraft motion for entry into departed flight. This approach was cost effective, and the risk was low.

The distortion levels presented to the engine face were measured by the special 40-probe total-pressure measurement rake. These data characterized the time-variant inlet distortion levels.

Test Technique

- **Twelve high yaw rate departed flight maneuvers (six nose-left, six nose-right).**
- **Progressively increasing entry yaw rates.**
- **Fixed engine throttle.**
- **Departure entry at an altitude of 35,000 ft and Mach 0.3.**

The throttle lever angle was set at military power (the maximum non-after-burning setting) for entry into the departed flight maneuvers. All stalls recovered without pilot action. The only time that the throttle was moved was during the aircraft recovery phase. At this time, the throttle was reduced to the idle position.

The departed flight testing was completed in a series of three flights during a period of 1 day. These tests were flown by two pilots.

Test Matrix

Direction	Entry yaw rate, (deg/sec)	Engine response
Nose-left	-41	Stalls (2) on right-hand
Nose-left	-52	Stall-free
Nose-left	-64	Stall-free
Nose-left	-67	Stall (1) on right-hand
Nose-left	-87	Stall-free
Nose-left	-91	Stalls (1) on left-hand and (9) on right-hand
Nose-right	45	Stall-free
Nose-right	57	Stall-free
Nose-right	64	Stall-free
Nose-right	71	Stall-free
Nose-right	81	Stall-free
Nose-right	91*	Stalls (2) on right-hand

*Example used for illustration in subsequent data figures.

The aircraft exhibited differing motions dependent on whether departures were initiated from a nose-left or nose-right condition. This difference is under review. The forces imposed by the gyroscopic moments of the engines' rotors may play a role in this behavior.

Test Matrix (concluded)

- **Aircraft attitude and motion in space defined by**
 - **Pitch angle, roll angle, heading angle.**
 - **Pitch rate, roll rate, yaw rate.**
- **Resulting inlet distortion levels presented to engine are functions of**
 - **Aerodynamic attitude, such as angle of attack, angle of sideslip, and possibly their rates.**
 - **Flight velocity.**
 - **Engine airflow.**

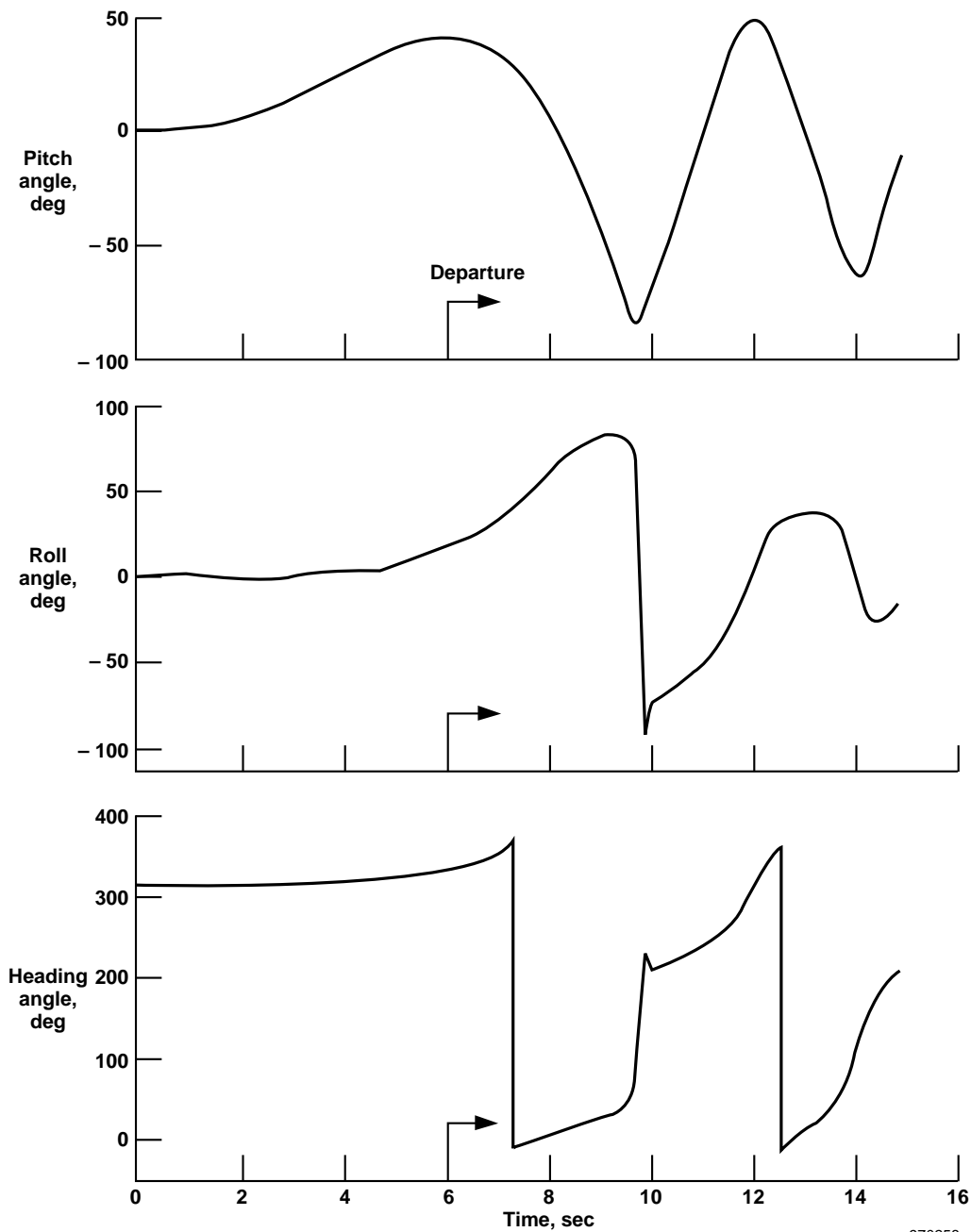
Particular attention was placed on the details of the aircraft attitude and motion. It may be possible to relate these details to the engine stall experience. They are more easily and reliably measured on typical production or research aircraft than aerodynamic flowstream descriptors. Measuring these descriptors requires specialized instrumentation and data acquisition system.

Analyses and Results

- **Aircraft attitude and motion obtained from inertial navigation system (INS) measurements.**
 - **Examples are shown in figures 1(a) and 1(b).**
- **Aerodynamic flowstream descriptors obtained from NASA's trajectory reconstruction analysis.**
 - **Angles of attack (AOA) and sideslip (AOSS) and their rates.**
 - **Examples are shown in figures 2(a) and 2(b).**

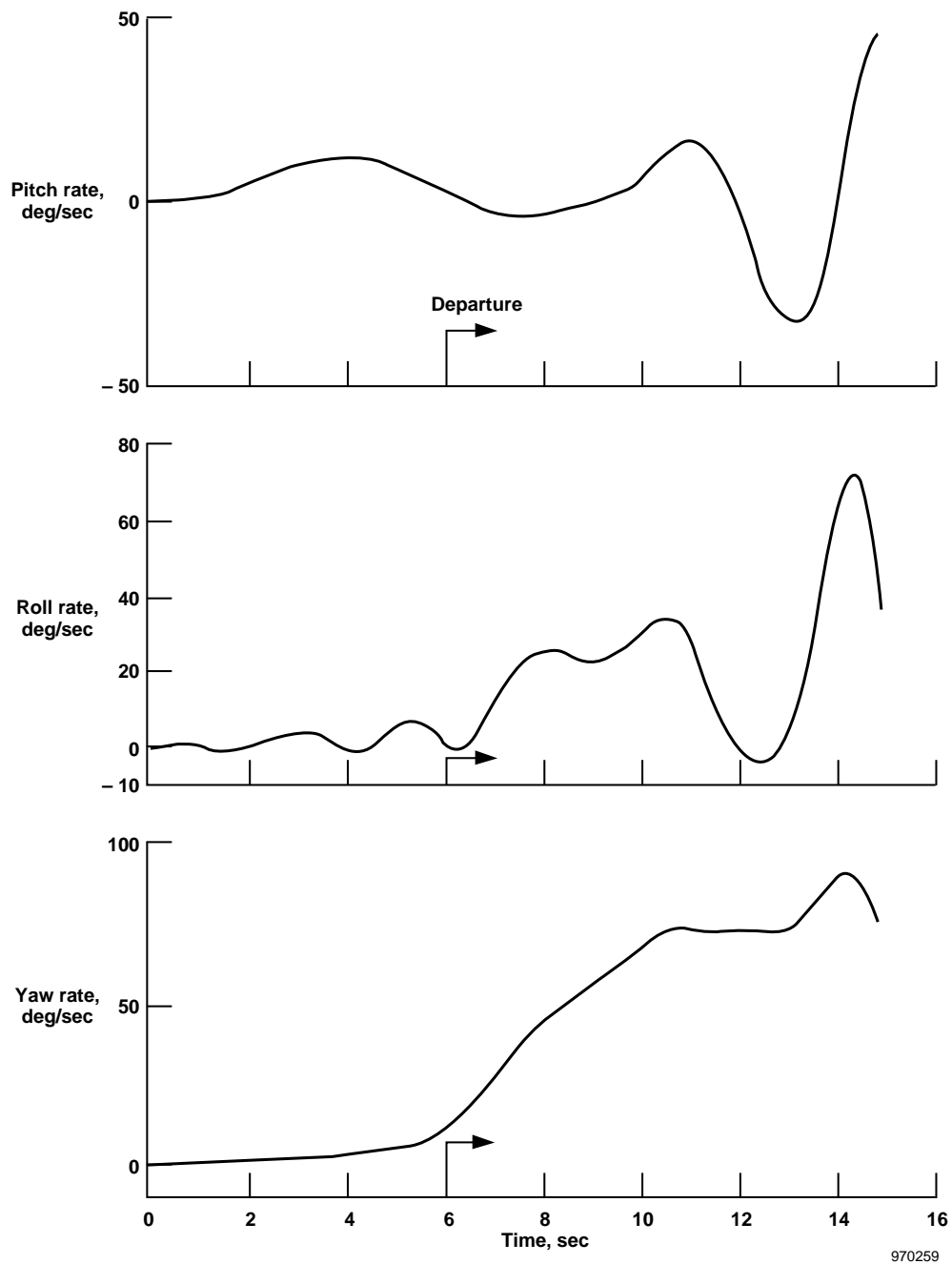
Analyses and Results (continued)

Figure 1(a). Aircraft attitude obtained from INS measurements.



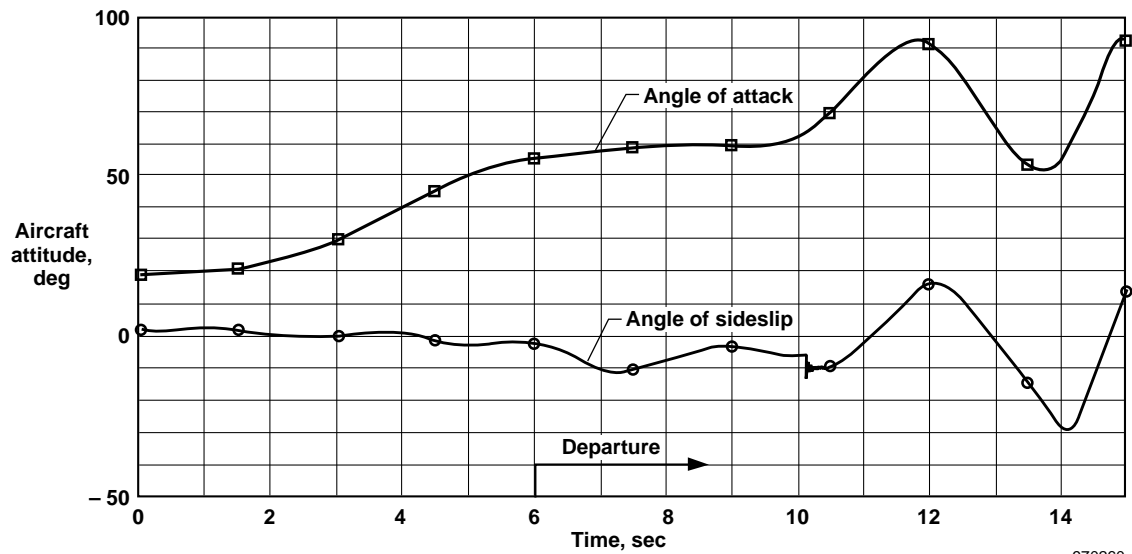
Analyses and Results (continued)

Figure 1(b). Rate of change in aircraft motion obtained from INS measurements.



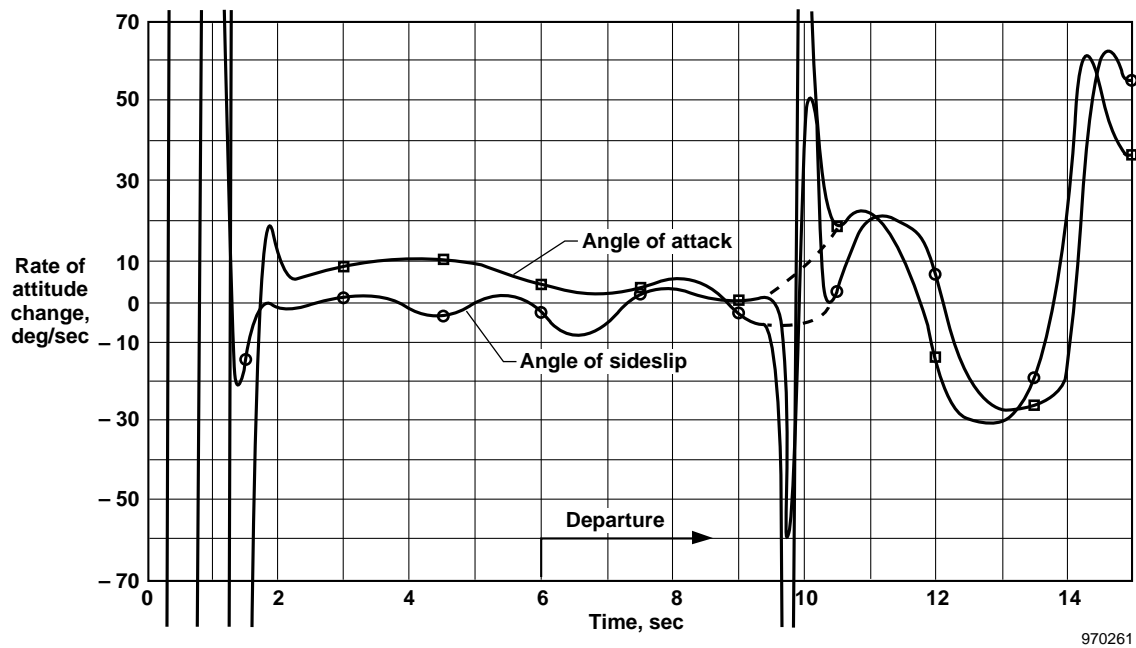
Analyses and Results (continued)

Figure 2(a). Aerodynamic flowstream descriptors obtained from NASA's trajectory reconstruction analysis for AOA and AOSS.



Analyses and Results (continued)

Figure 2(b). Aerodynamic flowstream descriptors obtained from NASA's trajectory reconstruction analysis for rates of change in angle of attack and angle of sideslip.



Analyses and Results (continued)

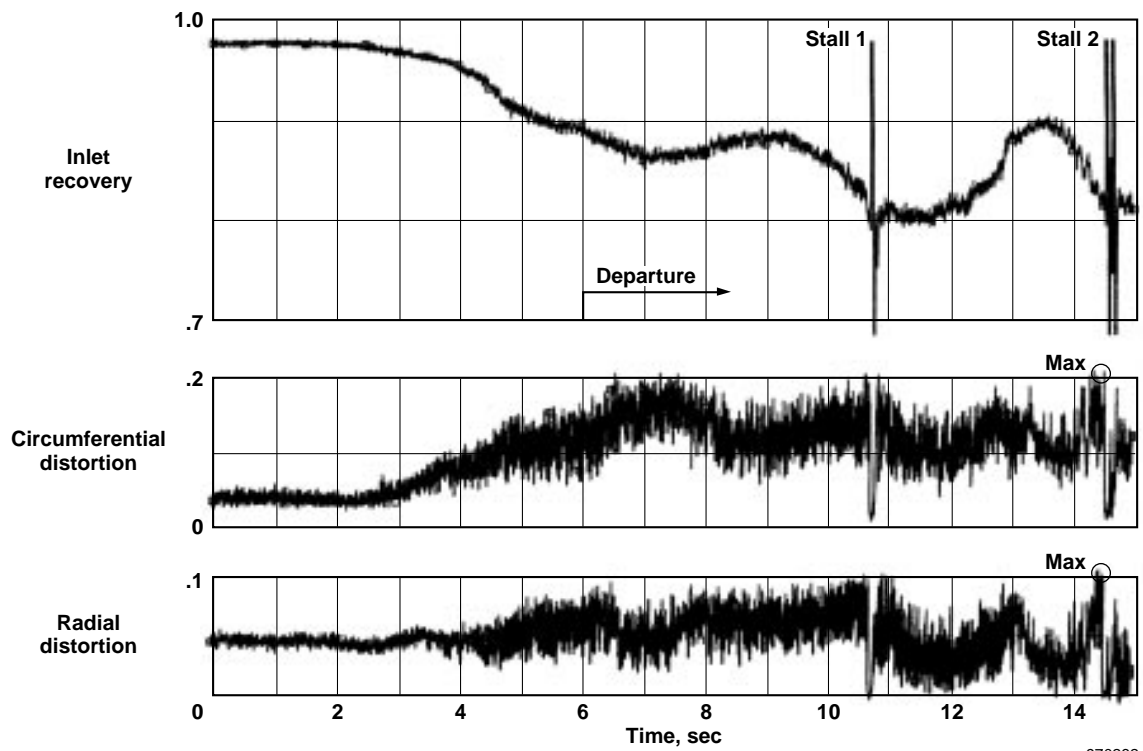
- **Engine entry airflow quality was characterized by inlet rake measurements in the form of inlet total-pressure distortion (spatial) and performance descriptors.**
 - **Circumferential (DP/PC) and radial (IDR hub, IDR tip, IDR max) distortion descriptors.**
 - **Inlet pressure recovery.**
 - **Examples are shown in figure 3.**

The presence of spatial inlet total-pressure distortion affects the engine's fan and compressor stability limits. Both the magnitude and the combination of circumferential and radial total-pressure distortion levels are factors to be considered. The inlet total-pressure data acquisition and processing techniques used were consistent with procedures specified by General Electric Aircraft Engines for the F404-GE-400 engine system. A distortion methodology is used to assess the predicted change in compression components stability lines (Δ PRS) resulting from the effects of inlet total-pressure distortion. The higher the level of Δ PRS, the greater the risk of engine stall.

Inlet pressure recovery is a non-spatial variation. The recovery level affects installed thrust, but its rate of change can affect engine stability.

Analyses and Results (continued)

Figure 3. Measured time histories of inlet and engine entry descriptors for airflow quality and performance for a stall event.



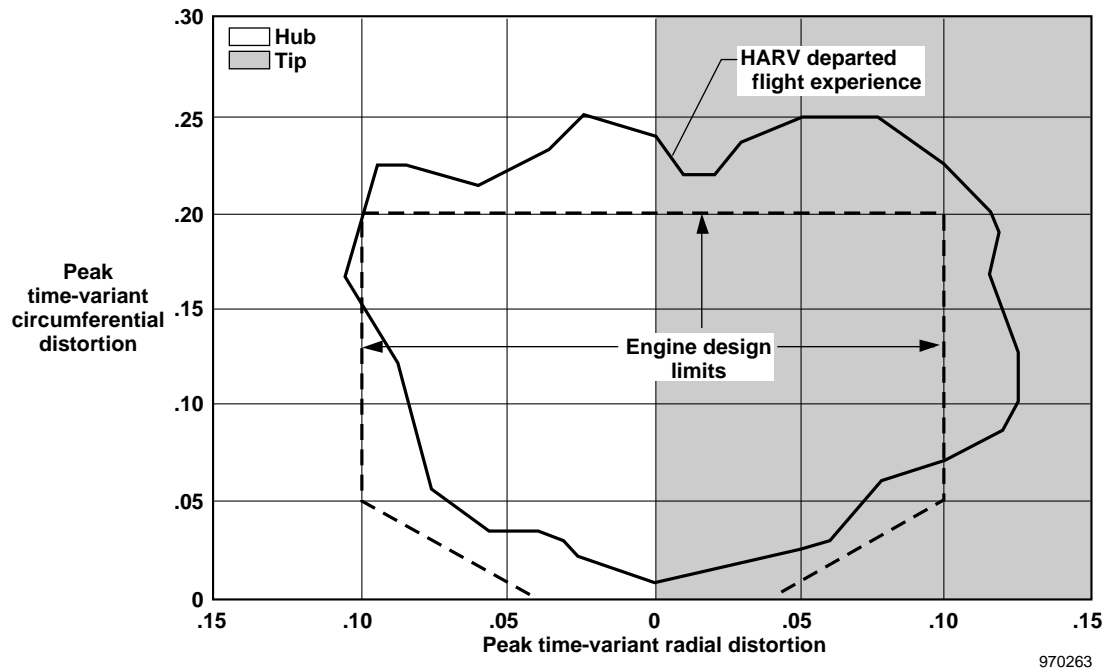
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Analyses and Results (continued)

- **An examination of the peak time-variant circumferential and radial total-pressure distortion levels that occurred during the maneuvers shows**
 - **Peak circumferential levels were limited in magnitude to 0.22 to 0.25.**
 - **In 11 of the 12 cases, the maxima were >0.2 (fig. 4).**
 - **Peak tip radial distortion levels were limited in magnitude to 0.10 to 0.12 (fig. 4).**
 - **Departure entry rate, direction, or length of data record were not a factor in the resulting magnitude of the distortion level for these cases.**
 - **Maximum observed peak hub radial distortion level recorded was >0.1 . However, higher levels could possibly occur (fig. 4).**
 - **Stall events did not correlate with the magnitude of the distortion, or ΔPRS , levels alone. Other factors appear to be involved.**

Analyses and Results (continued)

Figure 4. Peak time-variant circumferential and radial total-pressure distortion levels experienced during departed flight and the F404-GE-400 engine design limits.



During departed flight, the magnitude of the peak time-variant total-pressure distortion levels exceeded the design limits of the engine.

Analyses and Results (continued)

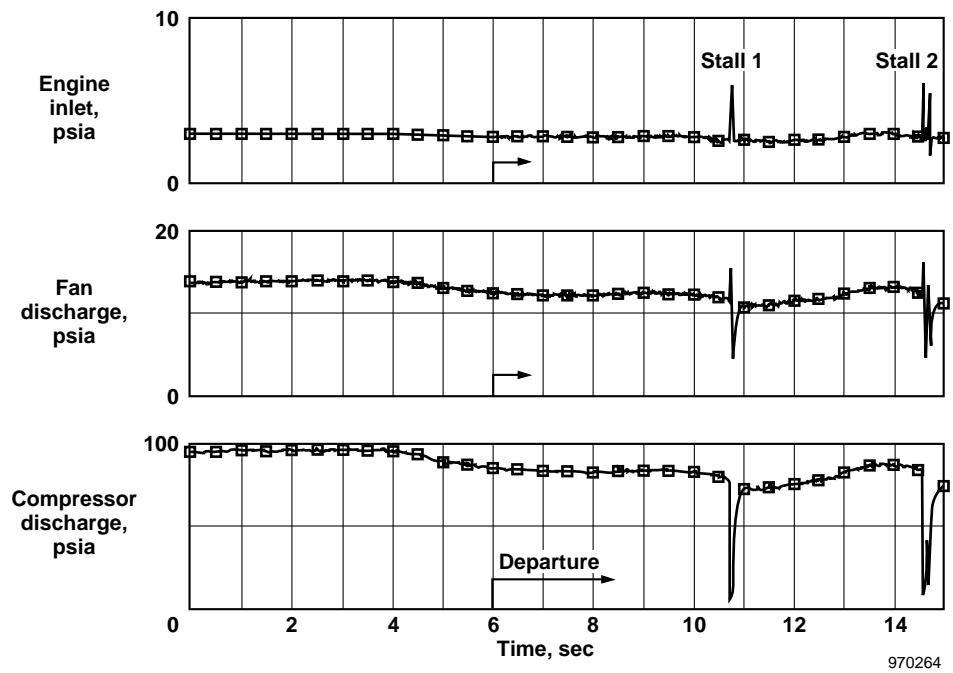
- **The resulting engine behavior during the maneuvers was described by the inlet and engine measurements.**
- **Based on the inlet sensor measurements, no temperature ingestion from the engine exhaust occurred before any of the stall events.**
- **An example of the measured time-history pressure records is shown in figure 5.**

The stall-initiating engine component was identified from pressure measurements. There were two compressor discharge pressures, two fan discharge wall-static pressures, and eight inlet duct and engine entry wall-static pressures. A detailed examination of the relative phasing and the direction of the perturbation of their time-history records gives the sequence and propagation of the instability. All stall events were initiated by the compressor.

During the maneuvers, there were small perturbations in the engine operating condition that could have a destabilizing influence. These perturbations were not induced by the pilot.

Analyses and Results (continued)

Figure 5. Measured inlet and engine entry and engine internal pressure time histories for a stall event.



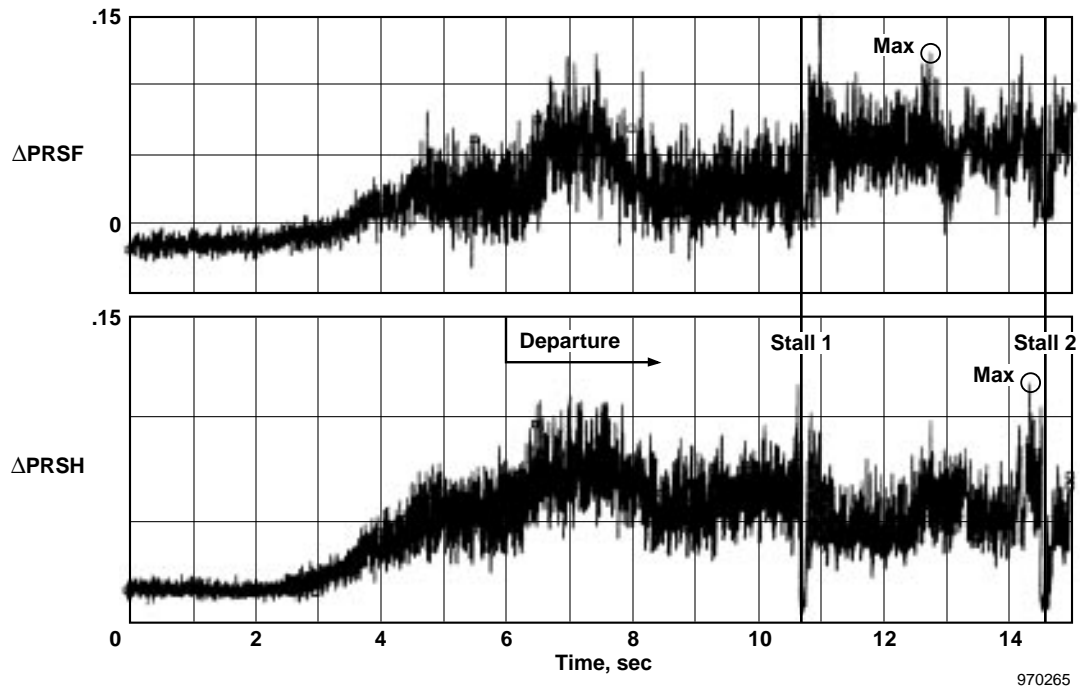
Analyses and Results (continued)

- **For the measured levels of inlet total-pressure distortion, the predicted loss in stability line (ΔPRS) was calculated for the compression components.**
 - **For the fan ($\Delta PRSF$).**
 - **For the compressor ($\Delta PRSH$).**
 - **An example of the results is shown in figure 6.**

The F404-GE-400 engine distortion methodology was used to assess the predicted change in compression components stability lines (ΔPRS).

Analyses and Results (continued)

Figure 6. The time histories of the predicted loss in stability line of the fan ($\Delta PRSF$) and compressor ($\Delta PRSH$) resulting from the measured levels of inlet total-pressure distortion.



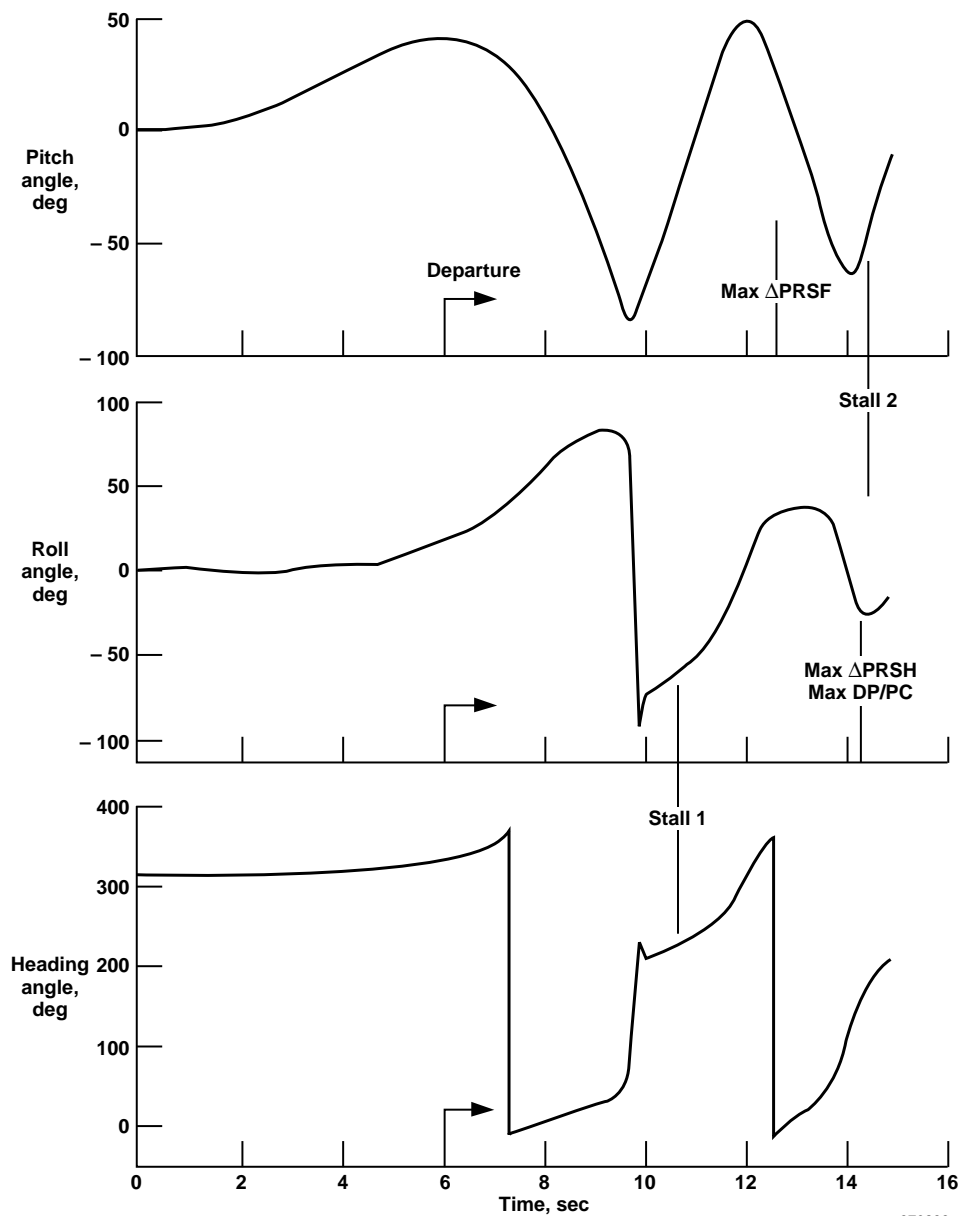
High levels of ΔPRS for the compressor were seen immediately before stall occurrences. However, many instances where high ΔPRS levels did not trigger a stall were also noted.

Analyses and Results (continued)

- **For the aircraft attitude and motion and the aerodynamic flowstream descriptors, the conditions were identified for**
 - **Maxima for inlet and engine entry total-pressure airflow quality descriptors.**
 - **Circumferential (DP/PC) and radial (IDR hub, IDR tip) distortion.**
 - **Maxima of the predicted loss in stability line (ΔPRS) of the fan ($\Delta PRSF$) and compressor ($\Delta PRSH$) resulting from the influence of spatial inlet total-pressure distortion environment.**
 - **Engine instabilities (if present).**
- **Examples for an event during which stalls were encountered are shown in figures 7(a) through 7(f).**

Analyses and Results (continued)

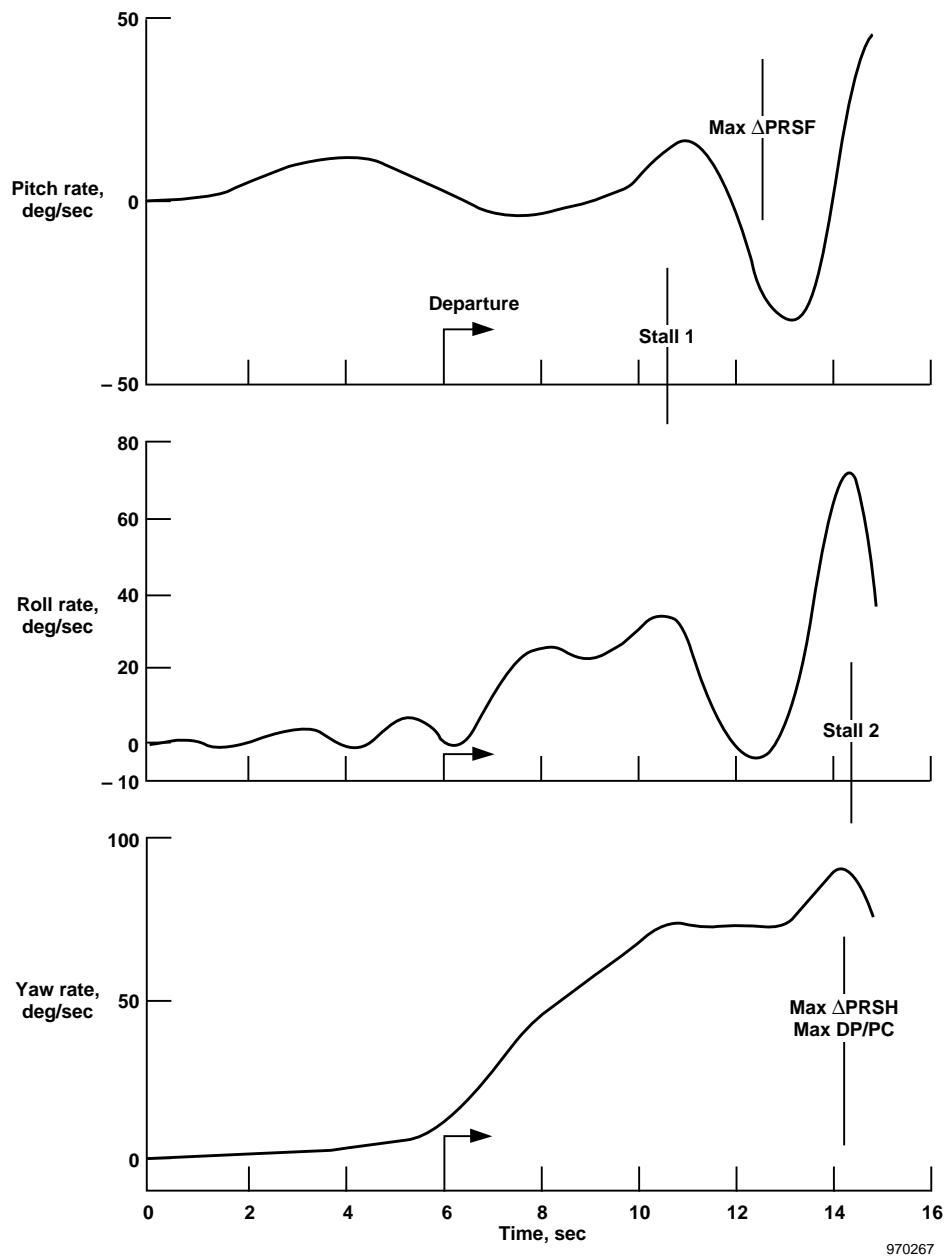
Figure 7(a). Identified conditions superimposed on the aircraft attitude time histories.



The aircraft attitude was not a factor in the stall events.

Analyses and Results (continued)

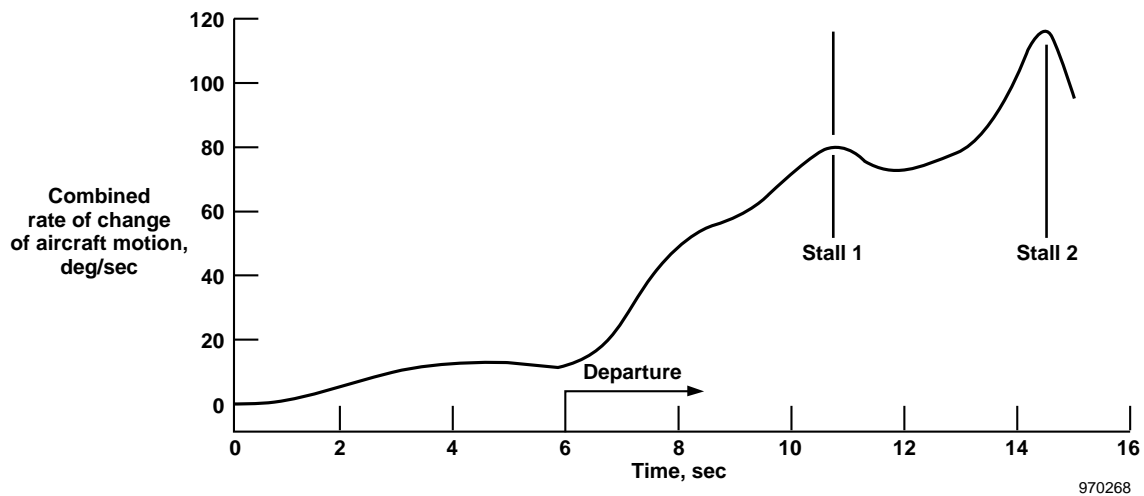
Figure 7(b). Identified conditions superimposed on the aircraft motion time histories.



The rate of change of the aircraft motion appeared to be a factor in the stall events.

Analyses and Results (continued)

Figure 7(c). Identified conditions superimposed on the combined aircraft motion time history.



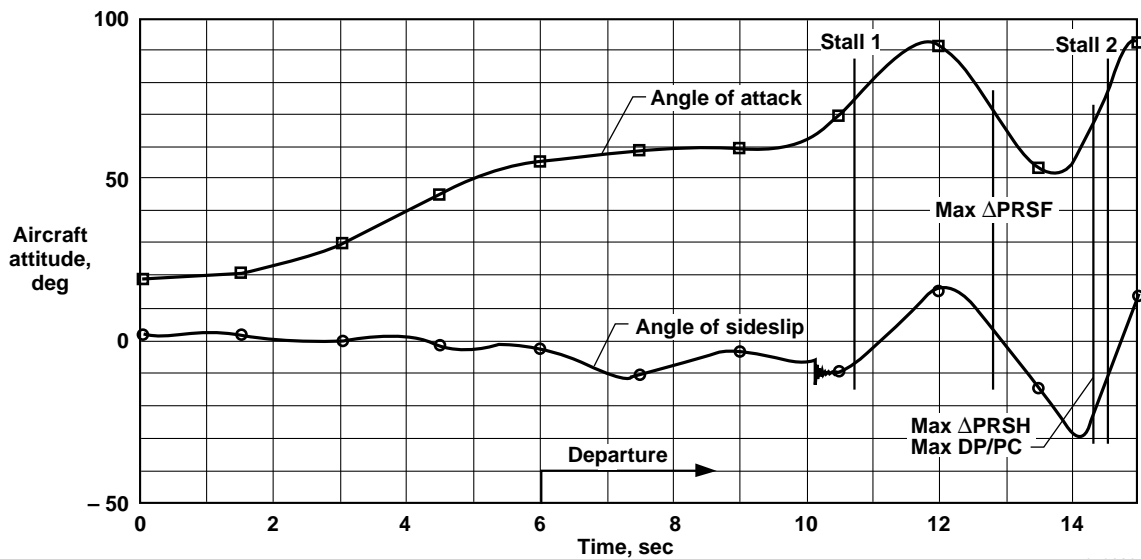
The combined rate of change of the aircraft motion appeared to be a factor in the stall events. The motion would affect the concentricity of the engines' airfoil running clearances and thereby reduce the compression components' stability limit lines.

The combined rate of change of aircraft motion is assumed to be described by

$$\{(\text{pitch rate})^2 + (\text{roll rate})^2 + (\text{yaw rate})^2\}^{0.5}$$

Analyses and Results (continued)

Figure 7(d). Identified conditions superimposed on the aerodynamic flowstream (AOA, AOSS) time histories.

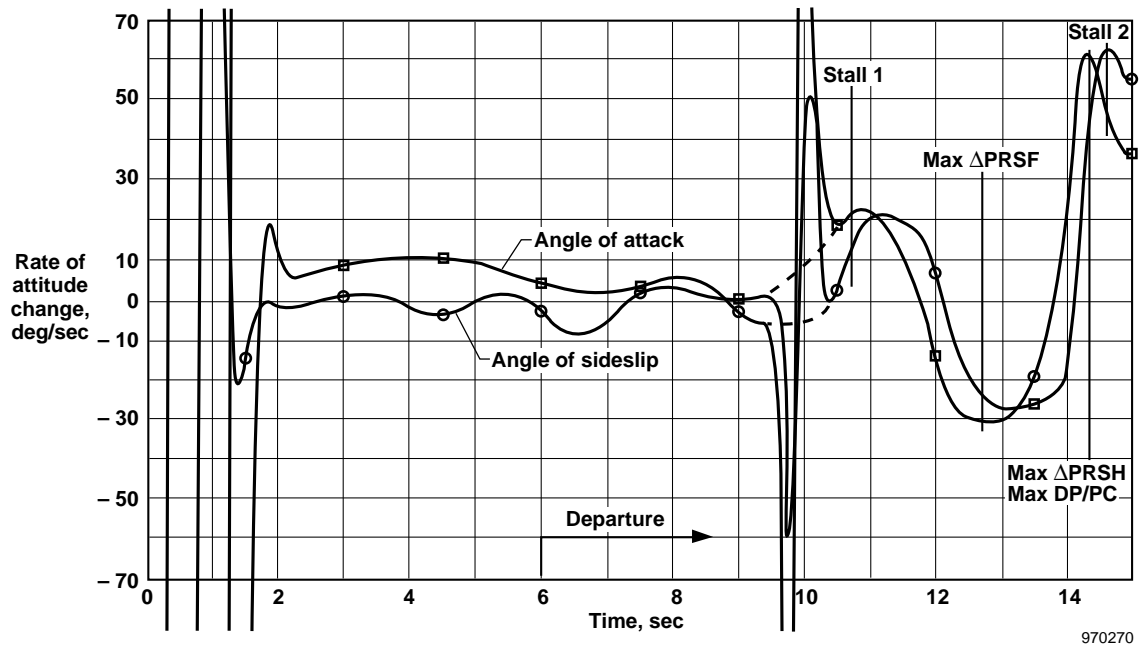


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Stalls occurred at high angle of attack (>70 deg) and a wide range of angles of sideslip. There was a possible dependence on angle of sideslip. Stalls tended to occur at a lower negative angle of sideslip (nose-right) for a given angle of attack. All events occurred at positive Mach numbers.

Analyses and Results (continued)

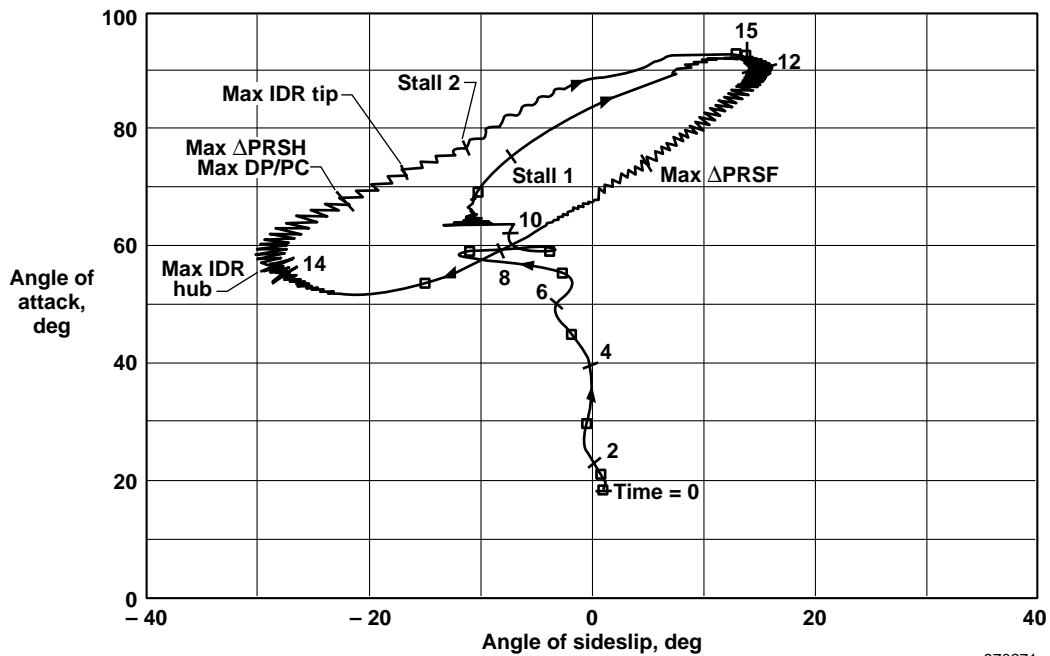
Figure 7(e). Identified conditions superimposed on the aerodynamic flowstream rate-of-change time histories.



The rate of change of the aerodynamic attitude was not a factor in the stall events.

Analyses and Results (continued)

Figure 7(f). Identified conditions superimposed on the aerodynamic flowstream (AOA, AOSS) trajectory time history.



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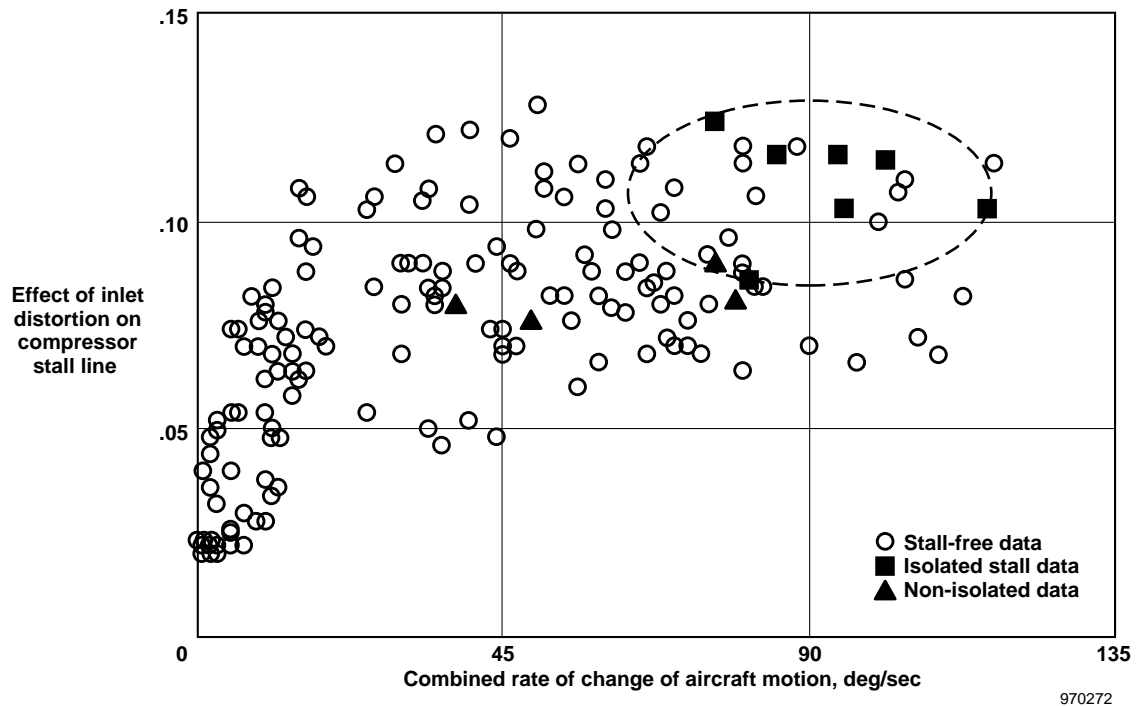
The change in the attitude of the aerodynamic flowstream with time was very slow when compared to the time scale (about 20 msec) for aerodynamic disturbances to propagate from the inlet lip to engine face.

Analyses and Results (continued)

- **If the combination of effects of time-variant inlet distortion (in terms of $\Delta PRSH$) and aircraft motion play a role in the resulting engine behavior, it should be possible to establish the relationship for their relative levels which result in non-stall or stall events.**
- **Such a relationship should include data from all the flight records.**
- **A summary of the relative levels is shown in figure 8.**

Analyses and Results (concluded)

Figure 8. Relative levels of the effects of time-variant inlet distortion (in terms of $\Delta PRSH$) and aircraft motion.



The engine stalls appear to be associated with the effects of high levels of time-variant distortion during high rates of aircraft motion.

Concluding Remarks

- **The objectives of the departed flight test campaign were achieved.**
- **During departed flight, the magnitude of the peak time-variant total-pressure distortion levels was well beyond those encountered in the normal operating regime for controlled flight.**
- **The peak distortion levels that were experienced were in excess of the design limits of the F404-GE-400 engine.**
- **When stalls did occur, they were initiated by the compressor.**
- **All stalls recovered without pilot action.**
- **The engine stalls appear to be associated with the affects of high levels of time-variant distortion during high rates of aircraft motion.**

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13. ABSTRACT (Maximum 200 words) The F404-GE-400-powered F/A-18A High Alpha Research Vehicle (HARV) was used to examine the quality of inlet airflow during departed flight maneuvers, that is, during flight outside the normal maneuvering envelope where control surfaces have little or no effectiveness. Six nose-left and six nose-right departures were initiated at Mach numbers between 0.3 and 0.4 at an altitude of 35 kft. The entry yaw rates were approximately 40 to 90 deg/sec. Engine surges were encountered during three of the nose-left and one of the nose-right departures. Time-variant inlet-total-pressure distortion levels at the engine face did not significantly exceed those at maximum angle-of-attack and sideslip maneuvers during controlled flight. Surges caused by inlet distortion levels resulted from a combination of high levels of inlet distortion and rapid changes in aircraft position. These rapid changes indicate a combination of engine support and gyroscopic loads being applied to the engine structure that impact the aerodynamic stability of the compressor through changes in the rotor-to-case clearances. This document presents the slides from an oral presentation.				
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